THE SYNTHETIC DESCRIPTION OF THE RESULTS, SCIENTIFIC ACHIEVEMENTS AND PRACTICAL APPLICATIONS THE EUREKA INITIATIVE, THE PROJECT IMPERJA, E3496!, IMPROVING THE FATIGUE PERFORMANCE OF RIVETED JOINTS IN AIR FRAMES

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The goal of the project was to increase the fatigue life of the riveted joints, which leads to an increase in the aircraft service life, a smaller number of inspections and, as a result, lower operating costs for an aircraft. It has been demonstrated that this goal can be achieved by the analysis and optimization of the riveting process as well as by improving the fatigue life prediction methods (crack initiation and propagation).

All activities in the aerospace area are subjected to regulations. Significant formal changes have taken place in the aircraft design regulations in recent years. The European Aviation Safety Agency, established in the EU in 2002, introduced the Certification Specification (CS), which contains the airworthiness code and acceptable means of compliance for the particular types of an aircraft. In 1997, in the US, the Code of Federal Regulations (CFR) was introduced relating to all areas of life including politics, law and economy. The aircraft design regulations are contained in the Title 14 CFR. The merit changes have taken place too e.g. the introduction of the damage tolerance as a basic methodology for commuter aircraft. The standard recommended by the Certification Specification and the Title 14 CFR are the American Society for Testing and Materials (ASTM) standards for material tests and the NASM1312 Standard Practice. Fastener Test Method standards for riveted joint tests.

The strong correlation between the service life and Direct Operating Costs (DOC) of the aircraft has been proved with the calculation carried out according to the methodology described in the book Airplane Design by Jan Roskam, part 1, 8. For example, extending the service life of the M28 Skytruck airplane from 8 000 to 32 000 hours could decrease its DOC to 47%, which should directly affect the aircraft price.

The IMPERJA project consist of two parts: basic and applied research.

The program of basic research was developed based on the wide literature available. The authors assumed that experimental and theoretical results should be valuable for the aircraft life estimation and manufacturing. Some previously examined research topics were repeated for sheets and rivets materials used in the aerospace industries in Central Europe.

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[1]http://www.eurekanetwork.org/project/-/id/3496

A wide range of tests of the materials used in the riveted joints were conducted. These covered monotonic and fatigue (high- and low-cylce) tests as well as examinations of fatigue crack growth. Two sheet materials (D16AT [and its variation D16CzATW] and 2024-T3), two types of anti-corrosion layer (alclad and anodised) and three rivet materials (PA24, PA25 and 2117) were compared. The tests performed enabled the comparative analysis of the above mentioned alluminium alloys used in the Polish aerospace industry (D16, PA24 and PA25) as well as two types of alloys used in the West (2024 and 2117).

The Portevin-Le Chatelier effect has been observed in the monotonic tests, especially for the specimens cut lengthwise to the rolling direction. This phenomenon was also visible in the the elevated temperature tests (for the range of 25°C to 200°C). During the tests, complementary methods were used: the passive IR-thermography and the acoustic emission. This allowed for widening the knowledge about the investigated materials. Moreover, the tear and shear tests for various squeezing forces were carried out.

The methodology of the residual stress measurements for the riveted joints with use of the XSTRESS3000 X-ray difractometer (XRD) was developed. This methodology allows elliminating the effect of the driven/manufactured head shadow on the measurements. An extensive program of residual stress measurements near the rivets was carried out. The measurements concerned specimens with varius types of rivets used in the PZL Mielec (countersunk and brazier, standard and with a compensator) and various riveting technologies (normal and NACA). The speciments were riveted with the force control. It has been demonstrated that rivets with compensators and the NACA technology cause higher compressive tangential stress on the manufactured head side. This significantly affects the fatugue life.

The strain measurements on the sheet surfaces near the driven heads during riveting process was carried out with strain gauges. The riveting processes were performed on the testing machine with the force control. The measurements were made for a 90º countersunk head rivet and a brazier rivet (standard and with a compensator). S-shaped[2] plots of strain as a function of squeezing force were recorded. This phenomenon was the most visible for the countersunk rivets. A similar shape of strain plots was presented by G. Li at all in paper [1].

The analysis of the Müller and Hart-Smith results [2,3] has indicated that when a 1,42-time increase in the squeezing force (from 12 to 17 kN, D/d parameter from 1,2 to1,5; where D-driven head diameter, d-rivet shank diameter) resulted in a twofold increase in the fatigue life, then a three-time increase in the squeezing force (from 12 to 36 kN, D/d parameter from 1,2 to 1,7) resulted in an eleven-time increase, and in case of riveting with the NACA technology, even an eighty-time increase in the fatigue life. The magnitude of the life increase suggests that the change of the joint formation mechanism has taken place. The working hypothesis has been assumed that, for the significant increase in the squeezing force, the plastic strain level necessary for adhesive joint formation (cold welding) has been reached. The destruction of an adhesive joint requires significantly higher force than that needed for the destruction of a mechanical joint. Consequently, the fatigue life of a riveted joint is much higher. The specimens with various types of rivets (countersunk and brazier, standard and with a compensator) and different riveting technologies (normal and NACA) were prepared at a wide range of squeezing forces. The standard anodised layer was removed in some rivets. So far investigations have demonstrated the existence of punctual and continuous joints on some part of the contact surface between the rivet and the sheet for the countersunk rivet with the anodised layer removed, for D/d=1,7. It is not certain, however, whether cold welding occurred in these joints.

[2]Reversal strain signal

The extensive FEM analyses of the riveting process were carried out. These covered static (with force control) and dynamic riveting. The axisymmetric and solid models were used. The material and geometrical nonlinearity was taken into account. The Stick-Slip Coulomb friction model (one of five implemented in the MSC MARC software) was chosen for the calculations, based on the numerical analyses. The materials models were developed based on the monotonic test. The results obtained from the axisymmetric and solid models were very similar, but the calculation time was incomparably shorter for the axisymmetric model. For frequently repeated analyses (e.g. optimization of the riveting parameters), axisymmetric models are the most convenient. The plots of radial and tangential stress and strain after riveting are consistent with the results obtained by Müller [2] as well as with the XRD and strain gauge measurements. Acceptable correlation of strain progress during riveting process in the calculation and the experiment (strain gauge measurements) has not been obtained, especially for tangential strains.

Rivets with compensators improve the transfer of the rivet material into the rivet hole and provide better hole filling in the sheet at the manufactured head side (the compensator causes a twofold increase in radial expansion of the rivet hole in the sheet, which means that radial displacements of the hole in both sheets are at the same level). Increasing the squeezing force value causes enlarging the plastic zone near the rivet. A considerably bigger effect can be obtained by restricting the driven head diameter (with the riveting set equipped with the ring) without changing its height. This causes a significant stress increase in the sheet, higher squeezing of the rivet shank in the hole and a more uniform stress distribution across the whole thickness of the sheet on the driven head side. Unfortunately, the difference between radial expansion of the hole in both sheets also increases, while the most desirable effect is when the radial expansion is at the same level in both sheets.

The numerical simulation of the riveting process has revealed monotonic decrease in averange contact stress and equivalent stress caused by an increase of backlash between the rivet and the hole edge (within the range indicated in the riveting manual). Moreover, in the case of the countersunk rivet, with high backlash, the filling of countersunk part of the hole is not sufficient, as is indicated by low contact stress values in that area.

Standard and reversed dynamic riveting techniques were compared by means of numerical simulations. Reversed riveting (riveting hammer on the side of the manufactured head with a compensator) is more appropriate since, in the case of standard riveting, at the first stage of the process an undisarable slit appears between the manufactured head and the sheet. According to the riveting manual, a special hold-on should be used for the rivet with a compensator. For example, in the case of the 3,55 mm brazier rivet with a compensator, the most benefitial filling of the rivet hole has been obtained for the hold-on radius of 10 mm (instead of 12 mm, as indicated in the manual).

The effect of the hole callibration (cold working – the local hardening of the hole and smothing the hole surface) on the fatigue life of the riveted joints was determined. The research was carried out for five levels of callibration. The fatige life of specimens with callibrated holes as compared to specimens with drilled or drilled and reamed holes was from 1,68 times (for the lowest level of callibration) to 11,4 times higher (for the highest level of callibration). The radial and tangential strain distribiution around the callibrated hole was determined with the Laser Grating Ekstensometry System. This technique was used during fatigue tests in order to determine the callibration influence on the local strain amplitude near the hole and near the hole filled with the rivet. For the structural specimens of the commuter aircraft, a fatigue life increase of 65% for lower load levels and of 112% for higher load levels was obtained.

A wide range of fatigue tests were carried out on the riveted lap joint specimens. The specimens represented the longitudinal joints on the aircraft pressurized fuselage. Fatigue properties of riveted joints were compared. The comparison concerned two sheet materials (D16AT and 2024-T3), two types of anti-corrosion layers (alclad and alclad+anodised) and three rivet materials (PA24, PA25 and 2117). The following design factors were considered in the fatigue tests: rivet pitch and row spacing as well as sheet thickness. The expedience of non-standard geometry of the riveted lap joint (staggered thickness joint-with stepped thickness) was examined. The effect of various squeezing forces was investigated for many of these configurations. Residual stresses around the rivet are proportional to the squeezing force value. The experimental investigation of the radial expansion of the rivet hole provided further information about the effect of squeezing force. The numerical calculation indicated that radial residual stresses are very sensitive to the removing of the rivet material (stresses decreased to 30% after removing the rivet), while tangential residual stresses remained at 80% of the previous state after removing the rivet. Radial displacements (diameter) of the hole were increasing while the rivet head was being removed and decreasing after the whole rivet shank was removed.

The fatigue tests have proved that the staggered thickness lap joints have better fatigue properties than standard joints. It should be emphasized that this is the first experimental confirmation of this interesting concept, which allows improving fatigue life without a weight penalty. The analyses with the Schijve model have proved that the main reason for this improvement is the reduction of the secondary bending in the outer rivet row, caused by the appropriate reduction of the sheet thickness.

An extensive program of measurements and analyses of load transfer in the lap joint was carried out in view of prospective fatigue life estimation. The program covered measurements of the lateral rivet forces in the overlap area and measurements of the rivet flexibility in relation to various squeezing forces. The results obtained enabled the verification of the currently used analytical solution of load transfer.

The fractographic analysis of the riveted lap joint has proved that the squeezing force affects the joint damage mechanism (due to the stress concentration at the hole or fretting phenomenon). The squeezing force influence should be thus taken into account in the fatigue life predictions. At the same time, the squeezing force influence on the load distribution in the joint has been proved. Therefore, the currently used analytical procedure of calculating the lateral forces in the overlap area could give incorrect results.

The new optical methods of the rivet deformations measurements were developed. They could be very useful for verification of the numerical calculations.

The theoretical analyses, confirmed with the strain gauge measurements, have indicated the presence of high secondary bending. Simple analytical methods based on the beam theory and described in the literature as a tool for estimating secondary bending in the riveting joints with the force eccentricity, the Schijve model in particular, have proved a convenient instrument for evaluation of the bending parameter, (defined as nominal bending stress in the critical rivet row divided by applied load). The validation of the Schijve model was carried out with the strain gauge measurements of bending stresses in the lap joint. The beam models' ability to adequately estimate the influence of the geometrical configuration and the load level on the secondary bending in the joints with the eccentricity was confirmed.

The FEM calculations of the lap joint and the single strap butt joint were performed. For the simple joint models, the sheets were modeled with shell elements, which lay in the sheet middle layer (secondary bending, which is the inherent feauture of such joints, was taken into account). Several rivets models were tested. For the analysis of the joint with many rivets, the model consisting of shell elements as well as the GAP contact elements and rigid MPC elements was developed. This model allows taking into account secondary bending as well as contact interactions between the sheets and the rivet shank with a relatively small number of nodes and contact elements. At the first stage of the analysis, temperature was defined for rivet elements in order to introduce residual stresses. At the second stage of the analysis, the joint was tensioned by applied force or displacements. The lap joint with two rivets (two rows) was analysed with the solid model. Geometrical and material nonlinearity was taken into account. At the first two stages, the sequential riveting process of two rivets was simulated. At the third stage, the joint was tensioned. Important strain changes on the sheet surface near the rivet were observed during tension. This phenomenon was recorded during the fatigue tests by the micro strain gauges placed in the specimen axis near the rivet manufactured head. Due to the problems with the calculation convergence, the results for high load level were not obtained.

The analysis of voids nucluated in the alluminium alloy during tension was carried out based on the SEM fractographic observations. The change in the material structure in the area of high tension was recorded. Cracks occur near the inclusions during tension of the sheet. Cracks appear at the boundary of the inclusions. In numerical simulations of structural elements, the materials are described in macroscopic terms e.g. the elasto-plastic material model which takes into account destruction of the material as a result of void growth, proposed by Gurson. This model enables a more realistic simulation of the sheet necking and observation of the slit growth during tension as well as a very exact determination of the sheet breaking moment based on the reaction value.

Comparative calculations of the stress intensity factor (SIF) for the corner crack growing from the hole – cylindrical and with the countersunk – in rectangle plates were performed using different methods. The Newman and Raju equations and FRANC3D (the boundary element method) software as well as the MSC MARC (the finite element method) software with the Virtual Crack Closure Technique (VCCT) were employed. Afterwards, the SIF calculation for a crack growing from one of the holes in the lap- joint specimen made of D16 alloy was performed. The fatigue tests of this specimen with crack growth measurement were carried out at the Krakow University Of Science And Technology (AGH), a member of the IMPERJA consortium. SIF Calculations for a few crack sizes were performed with the FEM and VCCT methods. The SIF for the complex load was determined as the superposition of the individual SIFs for each load component i.e. tension, bending and pin loading calculated in separate calculations. Moreover, crack growth predictions with the NASGRO equation implemented in the AFGROW software were carried out.

The possibility of fatigue life predictions with the estimated fatigue curves (in terms of strain and determined based on tensile tests) was investigated. This method was found unsuitable for 2024-T3 and D16CzATW aluminum alloy. Based on the selected loading sequence compiled with the FALSTAFF, seven methods of fatigue life estimation were verified. For the stress approach using the Wöhler diagram, the satisfactory correlation with the experiment results was obtained for the Kwofie's model. For the strain approach using the Morrow plot, the best results were obtained for the SWT parameter modified by Bergmann.

Application part of the project.

The variable amplitude (VA) fatigue tests were carried out for two types of specimens of the riveted joints in the wing and fuselage of the Commuter class aircraft .

The FEM analysis of the joint in the wing was performed at three different complexity levels, namely considering the part of the wing (three bulkheads at each side of the rib at the investigated joint, I level local model – the shell model of the joint corresponding to the specimen subjected to the fatigue tests, and II level local model – the solid model of the single rivet.

The cumulative fatigue damage calculations of the structural specimens were performed according to the method recommended by the USA Federal Aviation Administration in AC23-13A. The fatigue curves of riveted joint were derived from the literature and developed based on the fatigue tests performed under the IMPERJA project. The results of the FEM analyses of these specimens were used for the fatigue calculations with the MSC FAIGUE software. The high scatter and poor correlation with the experimental results were observed. In the calculations, the presence of the residual stresses after the riveting process was neglected. The residual stresses were taken into account in the fatigue calculations with the PragTic software (developed by J.Papuga, Evector company). The calculations were performed with the uniaxial (Smith-Watson-Topper, Landgraf) and multiaxial (Socie) methods. The obtained results were very conservative, especially for uniaxial methods (higher for the SWT than for the Landgraf methods; the methods differ in the way of the mean stress correction). The assumed material properties heavily influence the calculation results. The nodes of the numerical model with the lowest fatigue life were not always coincident with the points where the cracks nucleated in the experimental test.

Many practical results, which could be useful for the aerospace industry, were obtained. These concern appropriate selection of the rivet geometry, size and material as well as the riveting process parameters. Especially valuable is demonstrating the dependency between the squeezing force and the fatigue life of the joints. Higher squeezing force is connected with higher radial expansion of the rivet hole, which causes generation of the residual compressive stresses around the rivet – which is benefital from the fatigue point of view. The observation that the fatigue performance of the joint is determined by the squeezing stress rather than the relative size of the driven head, as it is commonly accepted in the industry, is of particular importance. The squeezing force effect should be taken into account in the fatigue life predictions since it influences the joint damage mechanism (due to the stress concentration at the hole or fretting).

Riveted staggered lap joints have better fatigue properties than standard joints. The fatigue tests have proved that fatigue life of the riveted joints is somewhat lower for the alclad and anodised sheets than for the alclad sheets. This observation agrees with the literature.

Based on the database generated under the project it has been demonstrated that for the lap joints of various geometrical configurations but the same sheet material, rivet type and squeezing stress, a good consolidation of the fatigue test results in the common scatter band is obtained when the fatigue lives are presented in terms of the combined tensile and bending stress amplitude.

The results of the research carried out under the project were published in one PhD thesis, six monographs (two in English) and two monograph chapters, forty-three articles (sixteen in English), forty-one conference papers (fourteen in English, presented at international conferences) and nineteen internal reports (four in English).

[1] Li, G., Shi, G., Bellinger N.C. (2006). *Studies of Residual Stress in Single-Row Countersunk Riveted Lap Joints,* Journal of Aircraft, Vol. 43, No. 3.
[2] Muller R. G. P. (1995). An experimental and numerical investigation on the fatigue behaviour of fuselage riveted lap joints, PhD thesis, Delft University of Technology.
[3] Müller R. P.G., Hart-Smith L.J. (1997). *Making fuselage riveting lap splices with 200-year crack-free fatigue life*. ICAF 97` „Fatigue in new and ageing aircraft". Proceedings of the I9-th Symposium of the International Committee of Aeronautical Fatigue, Edinburgh, EMAS Publishing, 499-522.